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High Power Operation of a Nitrogen Doped, Vanadium Compensated, 6H-SiC, Extrinsic Photoconductive Switch

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We report the high power operation of nitrogen doped, vanadium compensated, 6H-SiC, extrinsic photoconductive switches with improved vanadium and nitrogen dopant density. Photoconductive switching tests are performed on a 1mm thick, m-plane, switch substrates at switch voltage and currents up to 17 kV and 1.5 kA, respectively. Sub-ohm minimum switch on resistance is achieved for peak optical intensities ≥ 35 MW/cm^2 at 532 nm applied to the switch facet. A reduction of greater than nine orders of magnitude is observed in switch material resistivity between dark and illuminated states.

I. Introduction

Vanadium compensated, semi-insulating, 6H Silicon Carbide is an attractive material for construction of compact, high voltage, extrinsic, photoconductive switches due to its wide bandgap (3.0 eV), high dark resistance (> 10^8 Ohms), high critical electric field strength (2.5 MV/cm), high electron saturation velocity ($2.0\text{x}10^7$ cm/s) and high thermal conductivity (4.9 W/cm °C). The vanadium compensated, extrinsic, 6H-SiC photoconductive switch is transitioned into a low impedance on state by optically exciting carriers from extrinsic levels into the conduction and valence bands using below bandgap light. Previous work has demonstrated the feasibility[1,2] of vanadium compensated, 6H-SiC, extrinsic photoconductive switches and suggested methods to improve switch performance. Our present work focuses on determining the high power performance of vanadium compensated, 6H-SiC, extrinsic photoconductive switches with improved densities of the nitrogen and vanadium dopants. The two 6H-SiC photoconductive switches used in the high power tests were constructed using m-plane, square substrates with nominal thickness of 1 mm. The switches are designated m-6 and m-9. The m-6 (m-9) substrate is 1.02 (1.01) mm thick, 10.35 (10.31) mm in length along the a-plane and 9.77 (9.94) mm along the c-plane. The 9.77 (9.94) mm long c-plane facets were polished to an optical finish and the a-plane facets were ground to a planar finish. The m-6 and m-9 substrates have average densities of 2.30×10^{17}, 1.42×10^{17} and 1.80×10^{15} cm^{-3} of vanadium, nitrogen and boron, respectively.

The substrates were degreased, etched, and subsequently metalized in an electron beam evaporation system. The 0.75 cm diameter contact metallization is n-type and applied to opposing sides of the substrate. The initial metal layer is 100 nm of nickel, which is annealed at 1000 °C for two minutes to form a nickel-silicide[3] layer at the substrate surface. The remaining metal layers of 100 nm of titanium, 200 nm of platinum and 500 nm of gold are deposited on top of the annealed nickel layer on both sides of the substrate.

The dark current of the metalized substrates is measured using a system that has been described previously[1,4]. The dark current for the m-6 and m-9 substrates is plotted as a function of DC bias voltage in Figure 1. The dark current is a linear function of bias voltage for both the m-6 and m-9 substrates. Material resistivities of 1.85×10^{10} and 1.44×10^{10} ohm – cm are calculated for the m-6 and m-9 substrates, respectively.

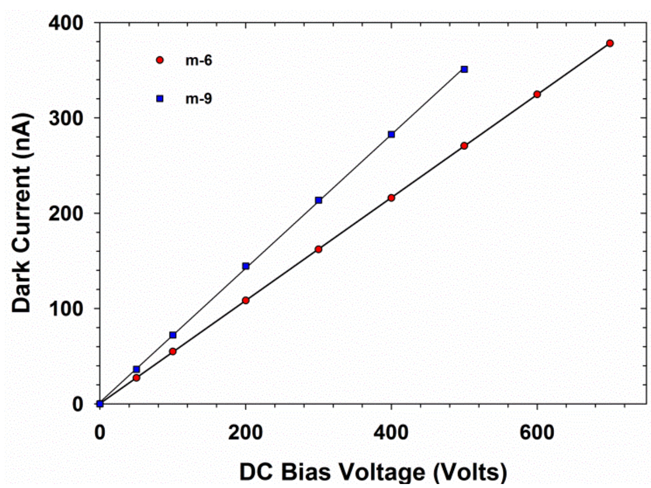

Fig. 1. Metallized substrates m-6 and m-9 dark current plotted as a function of bias voltage. The dark resistance and resistivity of the m-6 (m-9) substrate are 1.85e9 (1.42e9) ohms and 1.84e10 (1.44e10) ohm – cm.

The metalized m-6 and m-9 switch substrates were tested in the low voltage test circuit diagrammed in Figure 2, where the inductance ($L_{circuit}$), capacitance ($C_{storage}$), load resistance (R_{load}), and charge voltage (V) are 20 nH, 1.5 μF, 50.8 ohms, and 270 volts, respectively. Optical pulses of equal peak power were applied across the central 9 mm portion of the two, a-plane facets as shown in Figure 2. The 532 nm optical pulses slightly overfill the ~ 1 mm tall facets.

The optical pulse width is 8.8 ns FWHM and the peak power ranged from 0.10 to 2.01 MW at each of the two a-plane facets. The photoconductive switching results for the m-6 and m-9 substrates are virtually identical, consequently, detailed switching results will be presented for the m-6 substrate only.

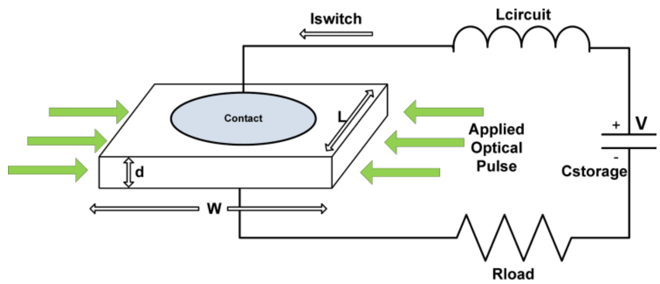

Fig. 2. Diagram of 6H-SiC photoconductive switch test circuit

Figure 3 shows the switch photocurrent and applied optical power for the m-6 switch for a peak optical power of 2.01 MW applied at two opposing facets (4.03 MW peak power total at 532 nm). The minimum switch resistance is calculated at the maximum switch current where di/dt and the inductive voltage drop in the circuit are zero. The voltage across the switch (V_{switch}) is the difference between the capacitor voltage and the load voltage ($V - I_{switch} \times R_{load}$) at the instant of maximum switch current. The minimum switch resistance occurs at the maximum

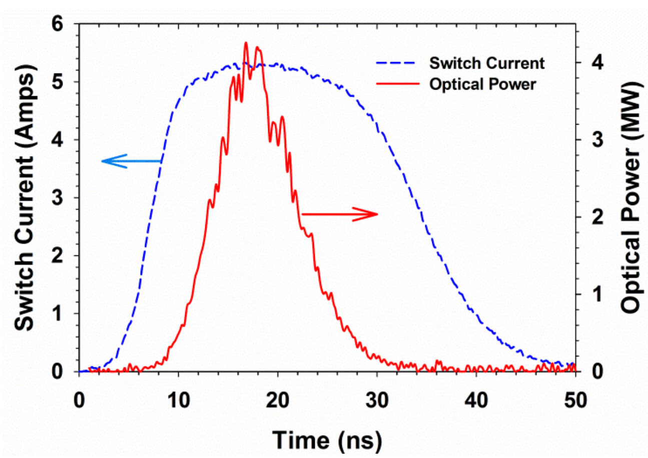

Fig. 3. Plots of photocurrent and optical intensity waveforms for m-6 switch for operation at charge voltage of 270 volts and peak optical intensity of 4.03 MW at 532 nm (2.01 MW at each a-plane facet).

switch current and is the ratio of switch voltage to switch current (V_{switch}/I_{switch}). The minimum switch current corresponds to the maximum optical intensity. The minimum switch resistance calculated for the m-6 switch from the data of Figure 3 is 0.66 ohms, which is at least nine orders of magnitude than its 1.85×10^9 ohm dark resistance.

The switch current and optical power waveforms of Figure 3 give the impression that the switch current precedes the optical power in time. This is not the case. This false impression is the result of the switch resistance being optically driven to a value that is much less than the load resistance. The switch resistance is 0.66 ohms at the peak optical power, which is more than a factor of fifty lower than the load resistance. The switch resistance is approximately equal to the 50.8 ohm load resistance at a value of optical power one fiftieth (2 %) of the peak optical power in Figure 3. The total resistance of the test circuit at one fiftieth the peak optical power of Figure 3 is ~ 100 ohms, which corresponds to a switch current of 2.7 Amps. The value of optical power required to obtain a switch current of 2.7 Amps occurs in the foot of the optical pulse leading to the false impression.

The maximum switch conductance is the inverse of the minimum switch resistance. Figure 4 is a plot of the maximum switch conductance as a function of total peak optical power at 532 nm for the m-6 switch. The maximum switch conductance increases linearly with total peak optical power for total peak optical power ≤ 3.0 MW and super-linearly for total peak optical power > 3.0 MW. We believe that the super-linear increase of maximum switch conductance with peak optical power is the result of electron-hole pairs being generated by self-two-photon absorption[5] (self-TPA) in the 6H-SiC substrate. The carrier generation due to self-TPA is proportional to βI^2, where I is the optical intensity transmitted into the substrate and β is the two-photon absorption coefficient. The 6H-SiC two-photon absorption coefficient, β, has been measured[6] to be 3.2 ± 0.3 cm/GW at 532 nm. The graph shown in the insert of Figure 4 shows a linear relationship between maximum switch conductance and the square of the peak optical power for peak optical power greater than 3.0 MW, which is expected for significant carrier generation by TPA. However, it should be noted that the calculated minimum switch resistance results become somewhat unreliable at resistances below 2 - 3 ohms. This occurs since we are subtracting the load voltage from the charge voltage, which are very close in value at high optical intensities. The matched voltage probes used for the load and charge voltage measurements both have an error of 2 percent. The precise value of the calculated switch resistance cannot be accurately obtained when the switch resistance falls below a value of a few percent of the load resistance (50.8 ohms), or, 2 – 3 ohms. That being said, all vanadium compensated, 6H-SiC, extrinsic photoconductive switches we have tested, regardless of vanadium and nitrogen density, have a super-linear dependence of maximum conductance on peak optical power at the 532 nm wavelength.

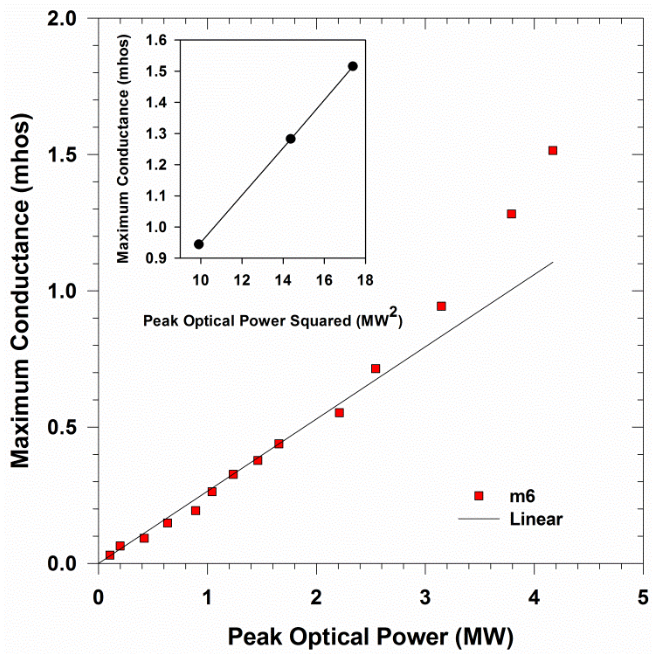

Fig. 4. The maximum conductance of the m-6 switch plotted as a function of peak applied optical power at 532 nm. The maximum conductance becomes super-linear at total peak applied power greater than 3 MW (1.5 MW at each a-plane facet). The insert is a plot of maximum conductance versus the square of peak optical power for optical power greater than 3 MW. The three points plotted in the insert correspond to the last three data points of the main plot.

II. High Voltage Tests

A high voltage version of the test circuit shown in Figure 2 was constructed for high power testing of the vanadium compensated, 6H-SiC, extrinsic photoconductive switches. A 9.9 nF, 20 kV rated storage capacitance ($C_{storage}$) was constructed using a series-parallel arrangement of 3.3 nF, 10 kV, NPO, ceramic chip capacitors. A 10.2 ohm load resistor (R_{load}) was constructed using ten parallel sets of two, 51 ohm, non-inductive, ceramic resistors with an 8 kV repetitive pulse rating. The calculated inductance of the high voltage test circuit is ~ 60 nH. The high voltage test board is submerged in a Flourinert[7] FC-77 bath to prevent surface tracking around the edge of the switch substrate. The high voltage test board storage capacitance is pulse charged to full voltage in 1 μs via a 2 μs wide, sinusoidal pulse. The optical pulse is applied to the switch facets when the charge voltage reaches maximum. High voltage tests are performed up to a charge voltage of 17 kV.

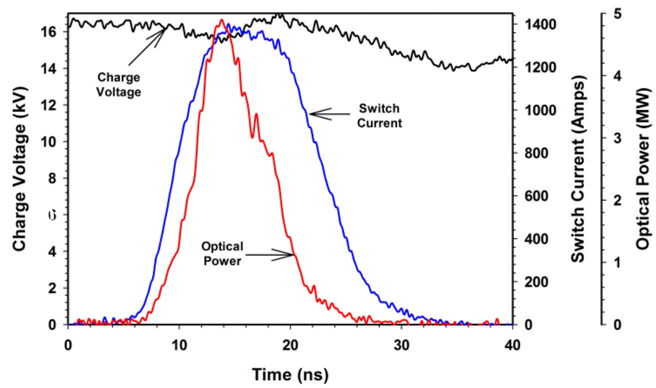

Fig. 5. Charge voltage waveform (top trace) at the time the m-6 photoconductive switch is fired. The peak charge voltage is 16.54 kV. The charge voltage was measured with a Tektronix P6015 high voltage probe. The load current waveform and optical power waveform are also shown.

The switch current, applied optical power and charge voltage on the high voltage test board storage capacitor for a peak charge voltage of 16.54 kV are shown in Figure 5. The switch is optically triggered at the peak charge voltage of 16.54 kV. The charge voltage is measured with a Tektronix P6015 high voltage probe. This probe has a 4 ns rise time and a bandwidth < 50 MHz, so the probe output does not give an accurate temporal response of the capacitor charge voltage after the triggering of the 6H-SiC. The peak switch current is 1401 amperes for a total peak optical power of 4.90 MW (2.45 MW applied to two facets).

It is difficult to calculate the minimum switch resistance since there is significant voltage droop on the charge capacitors during current flow through the photoconductive switch. This is due to increased charge being removed from the storage capacitors on the high voltage test board as a result of higher operating voltage, lower load resistance (10.2 ohms) and smaller value of storage capacitance (9.8 nF).

An estimate of the efficiency of the 6H-SiC photoconductive switch can be obtained by comparing the energy delivered to the 10.2 ohm load and the energy lost by the storage capacitor. The charge voltage on the modified high voltage board just before and after switch conduction is shown in Figure 6 for a peak charge voltage of 16.54 kV. The voltage droop in the capacitor voltage appears as step change in the charge voltage occurring just at the zero time mark in Figure 6, which is when the photoconductive switch is triggered. The duration of photoconductive switch current pulse is ~ 30 ns as shown in Figure 5. The initial capacitor

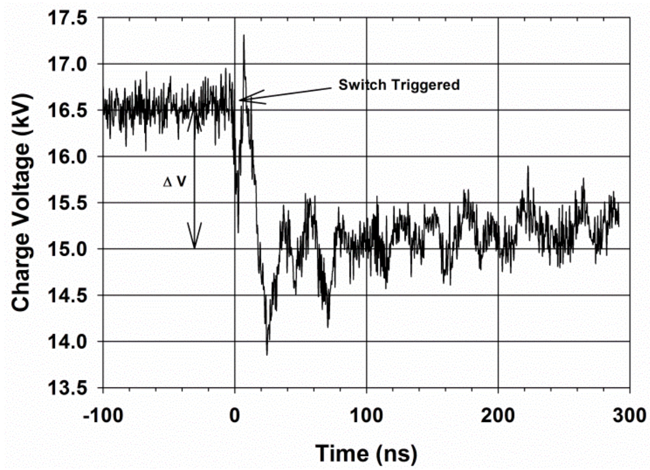

Fig. 6. Charge voltage (storage capacitor voltage) waveform plotted versus time for time interval just before and after 6H-SiC photoconductive switch current conduction. The voltage scale is in 500 volts per division. The switch is triggered at ~ 0 ns. The difference between initial and final capacitor voltage is ΔV.

voltage at the time the 6H-SiC photoconductive switch is fired is 16.54 kV. The final capacitor voltage, ~ thirty nanoseconds later, is 15 kV, obtained by averaging the oscillations on the capacitor voltage signal.

The switch efficiency can be calculated by comparing the energy lost from the storage capacitor to the energy transmitted to the load resistance. The energy lost from the storage capacitor is expressed in equation 1. Where V_i and V_f are the storage capacitor voltages at the beginning and end of the photoconductive switch pulse, respectively. Substituting the values

$$E_{lost} = C\frac{\left(V_i^2 - V_f^2\right)}{2} \tag{1}$$

listed above for V_i and V_f listed above we obtain a value of 0.238 J for E_{lost}.

The energy dissipated in the 10.2 ohm resistive load can be calculated using equation 2.

$$E_{load} = \int_{t_i}^{t_f} I_{load}^2(t) R_{load} dt \qquad (2)$$

Where t_i and t_f are the times that mark the beginning and end of the load current (I_{load}) and R_{load} is the 10.2 ohm resistive load. The current waveform (Figure 5) corresponding to the 16.54 kV charge pulse was numerically integrated and E_{load} was calculated to be 0.21 J. The switch efficiency is the ratio of E_{load} and E_{lost}, which is 0.882 (88.2%). The missing 11.8 % of E_{lost} is assumed to be dissipated in the 6H-SiC photoconductive switch. This is a reasonable switch efficiency considering the rate of rise and fall of the optical trigger pulse (see Fig. 5). The applied optical power is less than 3 MW for the first 5.5 ns and the last 10 ns of the pulse. The applied optical power was greater than 3 MW for 6 ns of the pulse duration. The peak optical power of 3 MW is the point when the minimum resistance of the switch used in this test (m-6) reached 1 ohm. As a result, the switch spends a fair amount of time with a resistance greater ≥ 1 ohm and a shorter period with a resistance < 1 ohm, ending up with an efficiency of 88.2 %. We can estimate the minimum switch resistance by numerically integrating the load current with respect to time up to the point that the load current reaches its maximum. This integral is the charge removed from the storage capacitor up to point in time when the switch current reaches its maximum. The storage capacitor voltage droop at the time the load current reaches its maximum is calculated using equation 3.

$$\Delta Q = \int_{0}^{\Delta t} I_{load}(t) dt = C \Delta V_c \qquad (3)$$

Where C is the value of the storage capacitor on the modified high voltage board (9.8 nF) and ΔV_c is the droop in capacitor voltage representing the decrease from its starting value (16.54 kV). The numerical integration of the load current for a peak charge voltage of 16.54 kV yielded a value of 7.841 μC for ΔQ. A value of 800.2 Volts is obtained for ΔV_c by dividing ΔQ by the value of the storage capacitor (9.8nF). The capacitor voltage at the point in time that the load current reaches its peak value is 15.74 kV, which is obtained by subtracting the voltage droop (800.2 Volts) from the starting voltage (16.54 kV). The circuit resistance of 11.23 ohms is obtained by dividing 15.74 kV by the peak current 1401 Amps. A minimum switch resistance of

1.03 ohms is obtained by subtracting the load resistance of 10.2 ohms from the minimum circuit resistance of 11.23 ohms.

Switch efficiency can be improved by increasing the rate of rise of optical power applied to the switch facets. A pulse-slicing Pockels cell and fast, high voltage, pulse generator are used to carve a sharp rise-time into the optical pulse used to trigger the photoconductive switch. Figure 7 shows a sharpened optical pulse (solid trace) and the resulting switch current (dashed trace) for switch operation at a charge voltage of 16.25 kV. The peak optical power is 4.9 MW which is split between two switch facets. The 10 – 90% rise-time of the optical power waveform is 1.27 ns. The corresponding 10 – 90% rise-time of switch current is 1.92 ns. The switch current rise-time is limited by the optical power rise-time and the L/R rise-time of the high power switch circuit. The maximum switch di/dt obtained for these tests is ~ 1 kA/ns. The switch efficiency calculated for the test shown in Figure 7 is 92 %. Increasing the optical power and decreasing the circuit inductance will further increase switch efficiency

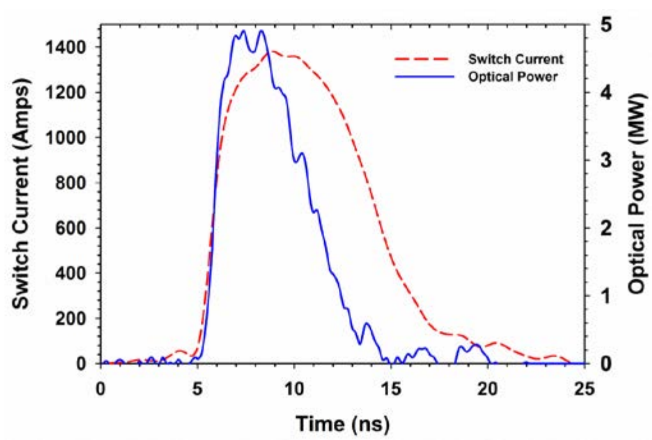

Fig.10. Optical power and photoconductive switch current waveforms plotted as a function of time for a ‘chopped’ optical pulse. The solid trace is optical power and the dashed trace is switch current.

The photoconductive switch fabricated from the m-6 substrate accumulated ~ 200 pulses at charge voltages ranging from 15 to 17 kV and 300 to 400 pulses with currents in excess of 1 kA without any discernable damage, or degradation in performance. The extrinsic photoconductive switches fabricated with vanadium and nitrogen doped 6H-SiC material have proven to be a high voltage, high power, compact switch capable of operation at high electric field gradient. The remaining development of this switch lies in electrode design and switch packaging to reduce voltage enhancements and enable switch operation at higher operating voltages. Switch efficiency can be improved by using optical pulses with faster rise and fall times and reducing circuit inductance.

III. Acknowledgements

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